Giant Magnetoresistance in a Single Thin Film of Permalloy

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Abstract

An experiment was constructed to measure giant magnetoresistance (GMR) in a 100-nm thick film of permalloy. After removing competing effects such as anisotropic magnetoresistance and eliminating all false positive signals, measurements indicate the presence of a domain wall but no definitive GMR signal. Alternative methods are in progress, which will hopefully resolve the difficulties with the initial measurement.

Introduction

Giant magnetoresistance (GMR) is a recently discovered member of a class of physical effects collectively referred to as magnetoresistance (MR), in which the resistance of a sample changes when the sample is placed in a magnetic field. Ordinary MR measurements produce a change in resistance on the order of 2%, while GMR measurements often produce a nearly 50% change, hence the qualifier "giant" [1]. The effect is usually observed in a system consisting of a thin layer of nonmagnetic material sandwiched between two ferromagnets. When current is applied through the layers of the stack and the angle between the magnetizations is varied, it is found that the resistance is a maximum when the two magnetic layers are antiparallel and a minimum when they are parallel. A diagram of a simple GMR stack is shown in Fig.1 below.

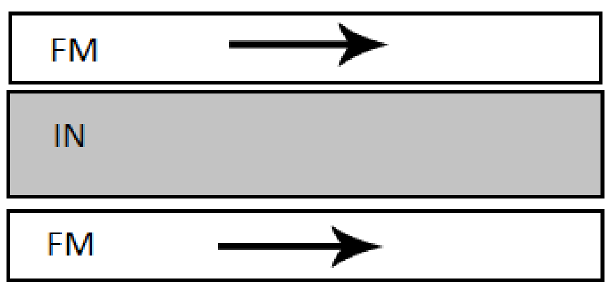


Fig. 1. A simplified schematic of a standard GMR experiment showing the two ferromagnetic layers (FM) and the insulator (IN) in between. In this diagram the two ferromagnets have parallel magnetizations, which leads to a low resistance state.

Since GMR is such a large, easily measureable effect, it has become the standard method by which hard drive read heads operate. Each bit is encoded as the direction of magnetization of a small magnet on the surface, either up or down, and the read head employs a GMR sensor while scanning over the surface to convert the changes in magnetic field into a change in voltage [2].

The goal of the present experiment was to observe the same effect in the simplest possible configuration: a single thin film. By applying two independent magnetic fields pointing in different directions to different regions of the sample, a domain wall between regions of different magnetization would form in the sample, analogous to the insulating layer in the GMR stack. By removing the layer of insulating material from the middle, we eliminate the potentially complicated surface effects between the layers and are able to examine GMR in a simpler system. One group has performed a measurement of GMR in a thin film of cobalt by magnetizing the film into a striped domain wall pattern and applying current perpendicular to the direction of magnetization [3], but no one has yet performed a convincing measurement through a single domain wall.

Theory

GMR is believed to originate in spin-dependent scattering of electrons within the stack [4]. The scattering coefficient of electrons traveling through the layers is dependent on the direction of magnetization in the material. If the direction of spin is antiparallel to the direction of magnetization, the scattering coefficient – and hence the resistance – will be much higher than if the spin and magnetization are parallel. In the limit that the thickness of the sample is small compared to the spin-diffusion length, analogous to the mean free path, we can treat the spin-up and spin-down electrons as independent channels. If the magnetizations of the ferromagnets are parallel, one of the channels (by convention defined as spin up) will pass through nearly unimpeded by magnetic effects while the other channel is heavily scattered. However, if the magnetizations are antiparallel, both spin up and spin down electrons will be scattered, resulting in a higher resistance overall. The functional form is measured to be [5]

$$\Delta R = R_0 + (R_A - R_P)\cos^2\left(\frac{\theta}{2}\right), \qquad (1)$$

where ΔR is the change in resistance, R_0 is a base resistance, R_A and R_P are the resistances in the parallel and antiparallel states, and θ is the angle between the magnetizations of the top and bottom layers.

Although we believe that GMR is caused by this spin-dependent scattering, it is not currently known if the scattering takes place in the bulk of the ferromagnetic layers or at the interface between the ferromagnetic layers and the non-ferromagnetic interior. By measuring the angular dependence of the resistance in a single thin film for different fields, it would be possible to compress the domain wall so that we could experimentally distinguish between the two possibilities: if the scattering took place at the interface within the domain wall, the angular dependence should become less significant as the strengths of the fields increased, while if the scattering took place in the bulk of the layers the fractional change in resistance would be independent of the strengths of the magnetic fields once saturation had been achieved.

Experimental Procedure

The sample used in the experiment was a 100 nm thin film of permalloy deposited onto a thin layer of bare silicon. The central region was about 20 μm long and 1μm wide, designed to be narrow enough so that a simple, single-cell domain wall could form in the middle. Four contacts on each side were placed along the length of this central region to precisely locate domain wall resistance. A cause for concern was the fringing fields of the permanent magnets, which were measured to extend about 0.75 cm beyond the edges of the magnets. To make sure that the length of the sample was greater than the extent of the fringing fields, four additional contacts were extended outwards from the central region so that the total length of the sample was about 1.3 cm. A diagram of the sample is shown in Fig. 2 below.

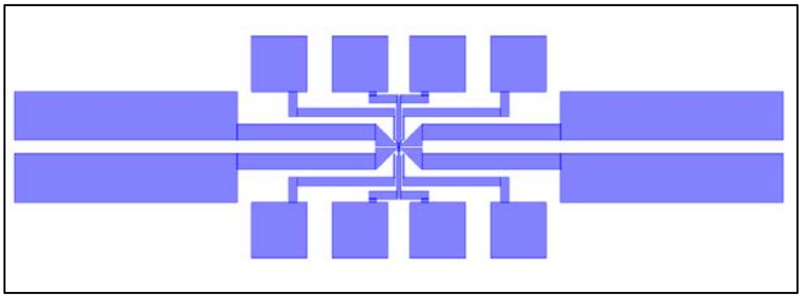


Fig. 2. A diagram of the sample – the white represents bare silicon and the purple deposited permalloy. Eight contacts are placed along the sample to locate domain wall resistance in the central region, while four additional contacts extended the length of the sample to about 1.3 cm to compensate for fringing fields of the permanent magnets.

The sample was patterned with optical photolithography in the Nanofabrication Center. The silicon surface was coated with a thin layer of photosensitive material, and then exposed to ultraviolet light through a specially prepared window so that the only bare spot on the surface was in the shape of the sample. Permalloy was then deposited on the material by sputtering in a high-vacuum system – the entire surface was coated, and when exposed to acetone the photosensitive material lifted off the sample while the permalloy adhered to the bare silicon.

In the experiment it was necessary to construct two separate magnetic fields so that the angle between them could be varied independently. One field was generated by a large electromagnet and the other by a pair of neodymium magnets placed about 1 cm apart, placed on a mobile stand as shown in Fig. 3 below.

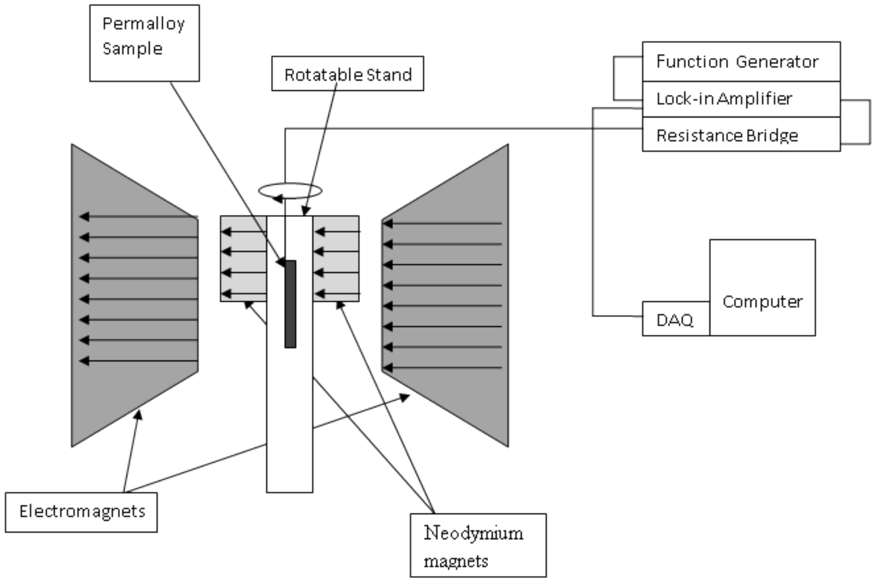


Fig 3. A schematic of the experiment, taken from [6]. In the diagram the permanent magnets are parallel to the external field, although they could be freely rotated about the axis shown.

Placing the sample between the permanent magnets proved to be a considerable technical challenge as the magnets would fly apart and twist in an effort to line up with the external field. Eventually a custom sample holder and a magnet holder were machined in the student shop to overcome the torque of the permanent magnets. The permanent magnets could be placed either parallel or perpendicular to the plane of the sample – a diagram of the two orientations is shown in Fig. 4. The perpendicular case was chosen since a greater magnetic field could be achieved with the permanent magnets and the fringing fields would be less significant, although the sample would be considerably more difficult to magnetize perpendicular to its plane.

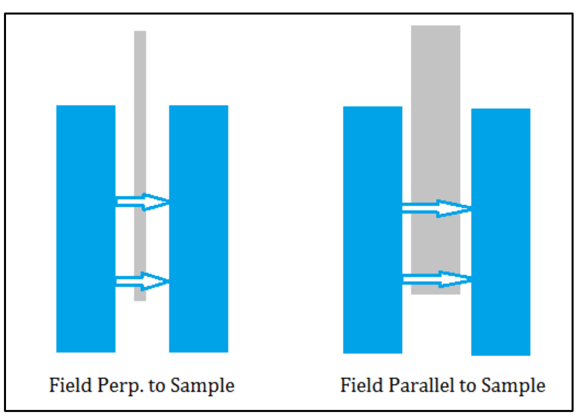


Fig 4. A diagram of the two possible orientations of the sample with respect to the direction of the permanent magnetic field. In the initial setup, the plane of the sample was perpendicular to the field to minimize the effect of fringing fields.

The resistance was measured by applying AC current from a function generator through the length of the sample and feeding the output into a four-terminal variant of a Wheatstone bridge as shown in Fig. 5.

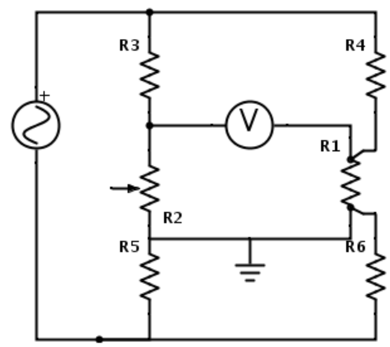
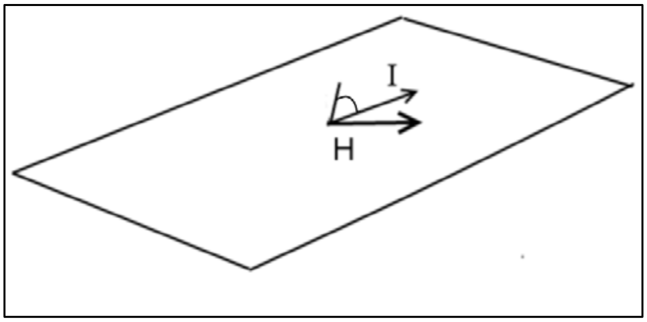


Fig 5. A schematic of the measurement circuit, which was essentially a four-terminal Wheatstone bridge. Using the bridge allows us to subtract off the base resistance and precisely measure changes in resistance on the order of 0.1% or less, while the four-terminal measurement minimized the effect of contact resistance. The voltmeter shown in the diagram was a lock-in amplifier.

Using the four-terminal Wheatstone bridge reduced the problem of measuring very small changes in an unknown voltage to simply measuring very small voltages, which is easily done with a lock-in amplifier. With the lock-in, a change of 0.01Ω could be easily measured.

Results

Magnetoresistance measurements were more difficult to interpret than had been anticipated, since in addition to GMR there is also the effect of ordinary anisotropic magnetoresistance, which produces a signal similar to GMR although it is a completely different physical phenomenon. AMR occurs whenever the angle between the current in a thin film sample and the magnetization of the sample is varied, and results in a minimum resistance when the current and the magnetization are parallel and a maximum resistance when they are parallel. In between, the resistance varies sinusoidally with the angle. To unambiguously demonstrate that GMR can occur in a single thin film, it was necessary to separate out the effect of AMR as well as ordinary domain wall resistance. For reference and to make sure that the sample was patterned correctly, the external field was set at 2 kG, large enough to saturate the sample, and the resistance was measured as a function of angle between the current and magnetization as shown in Fig. 6.



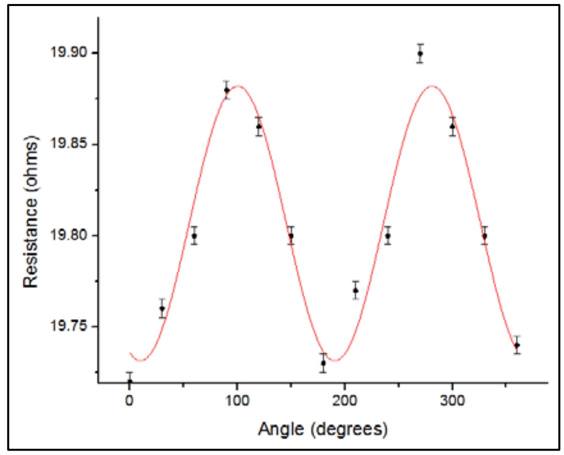


Fig. 6. On the left is a 3D schematic of the sample in the field, showing the orientation of the current with respect to the field, while on the right is an AMR plot of the sample resistance as a function of the angle between the current and the applied magnetic field.

As expected, resistance as a function of the angle follows a sine curve, indicating that the sample was fabricated and sputtered correctly. Afterwards, two AMR measurements were performed, with current parallel and perpendicular to the applied field, by sweeping the field from zero to saturation as shown in Fig. 7.

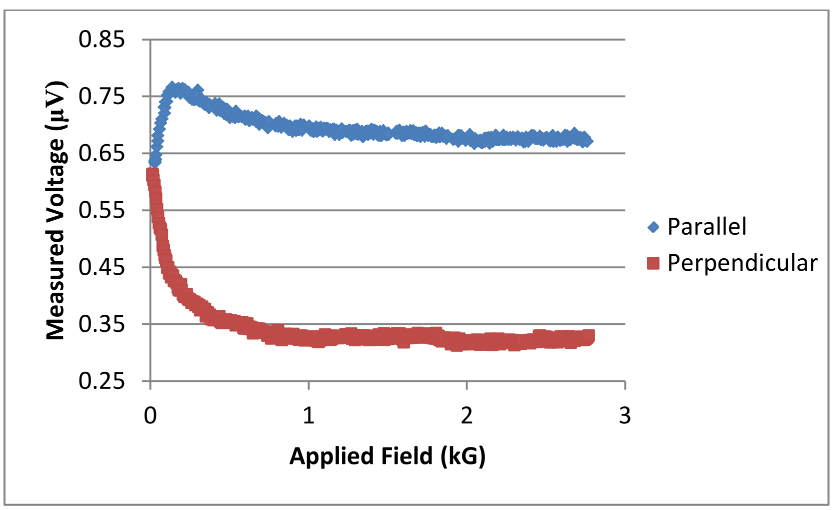


Figure 7. AMR effects obtained by placing the direction of current through the sample parallel and perpendicular to the applied magnetic field, and then sweeping the field. The voltage was measured with a lock-in amplifier and is proportional to the change in resistance of the sample. The maximum resistance change was on the order of 1%.

The maximum change in resistance was about 1%. Although the GMR experiment was designed to minimize AMR effects by always keeping the current perpendicular to the applied field, to definitively claim that GMR has been observed the signal must be greater than 1%. Initially, a sudden increase in resistance was observed in the antiparallel configuration when the external field reached 1 kG, but this signal was not repeatable. It was found later that in the antiparallel case the neodymium magnet, repelled by the external magnetic field, likely pressed against the delicate contact wires and caused an increase in resistance. After resolving this problem, no discernible increase in resistance either in the antiparallel state or the 90° state was observed, although the experiment was repeated several times at different heights of the sample with respect to the two opposing magnetic fields.

A small increase in resistance was observed when the sample was inserted between the permanent magnets, likely due to the formation of a domain wall within the sample. In the hope of compressing the domain wall, the sample was slowly inserted between the permanent magnets in the presence of the other external field, and the maximum change in resistance was measured as a function of the strength of the electromagnet field as shown in Fig. 8.

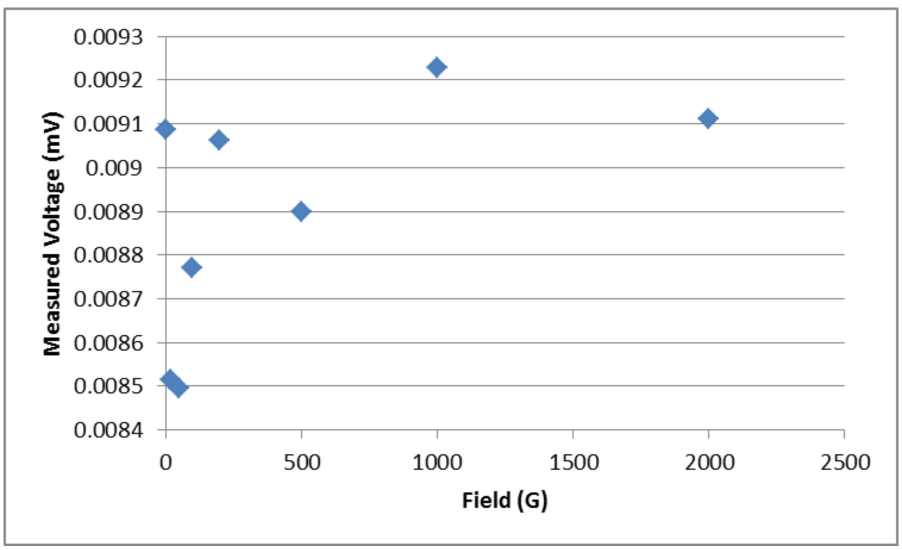


Fig. 8. The maximum change in voltage across the sample, proportional to the maximum change in resistance, when the sample is inserted between the permanent magnets, measured as a function of the external magnetic field. If the change were due to the formation of a domain wall, the maximum change should decrease as the external field increases. No such trend is observed, suggesting that the domain wall may not be stable or fully formed.

If the change were due to the formation of a domain wall, the maximum change would decrease as the external field increased. Results so far are inconclusive – it seems that a domain wall is formed but is not currently well controlled by the external fields.

Discussion and Future Work

The most likely explanation for the observed null result in the GMR measurement is that the field produced by the permanent magnets is insufficient to magnetize the sample through its thickness and perpendicular to the plane. Even if there were no GMR, we would still expect some increase in resistance due to formation of a domain wall between the upper and lower half of the sample, so it seems likely that a stable domain wall is not completely formed by the two opposing fields.

Currently the experiment is being rebuilt so that the field from the permanent magnets is parallel to the plane of the sample. Although the field from the permanent magnets is approximately halved due to the increase in separation, the sample should be much easier to magnetize parallel to its plane. Another possible solution is to sputter antiferromagnetic material over part of the length of the sample to pin the magnetization in place, although it may not be as easy to implement as simply performing the experiment in the other configuration.

References

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